Building and Environment 125 (2017) 319–325

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Seasonal trends of indoor fine particulate matter and its determinants in urban residences in Nanjing, China

Zhijuan Shao [a], Jun Bi [a], Zongwei Ma [a, *], Jinnan Wang [a, b, **]

[a] State Key Laboratory of Pollution Control & Resource Reuse, School of the Environment, Nanjing University, 163 Xianlin Avenue, Nanjing 210023, China
[b] State Environmental Protection Key Laboratory of Environmental Planning and Policy Simulation, Chinese Academy for Environmental Planning, 8 Dayangfang, Beiyuan Road, Chaoyang District, Beijing 100012, China

ARTICLE INFO

Article history:
Received 6 July 2017
Received in revised form
1 September 2017
Accepted 2 September 2017
Available online 5 September 2017

Keywords:
$PM_{2.5}$
Indoor air
Indoor-outdoor relationship
Seasonal variations

ABSTRACT

Most people spend more than 80% of their time indoors; thus, indoor air pollution has a significant influence on an individual's exposure to air pollution. In this study, $PM_{2.5}$ concentrations in both indoor and outdoor air were simultaneously measured in urban residences in Nanjing, China. The measurements were carried out using MicroPEM personal exposure monitors during summer, winter and transition seasons from March 2016 to February 2017. Information on building characteristics, occupants' activities and socioeconomic status (SES) variables was obtained through questionnaires during the sampling period. Significant seasonal variations in indoor and outdoor $PM_{2.5}$ levels were observed in this study, with the highest $PM_{2.5}$ concentration in winter and the lowest in summer. The correlation between indoor and outdoor $PM_{2.5}$ concentrations in transition seasons was higher than that in winter and summer. Linear regression models were fitted to log-transformed indoor $PM_{2.5}$ concentrations to determine potential influencing factors. Outdoor $PM_{2.5}$ was found to be the major source of residential indoor $PM_{2.5}$ pollution. The household activity of cooking was an indoor determinant of $PM_{2.5}$ concentrations in homes with open-plan kitchens or when the kitchen door was open during cooking. More frequent building ventilation could increase indoor exposure to outdoor $PM_{2.5}$ in transition seasons and winter or when the outdoor air quality is poor. SES variables such as dwelling ownership and household income were associated with indoor $PM_{2.5}$ concentrations.

1. Introduction

Fine particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) has become the primary air pollutant in most Chinese cities [1]. Exposure to $PM_{2.5}$ is associated with negative health effects, such as cardiovascular and respiratory diseases, cancer and preterm birth [2–4]. Although the air quality in China has been improving in recent years, $PM_{2.5}$ still ranks 5th among all risk factors for disability-adjusted life-years (DALYs) in China [5]. Only 19% of the population in China live in areas that meet the annual $PM_{2.5}$ standard metric of the National Ambient Air Quality Standards (NAAQS) [6]. In a recent study, it was estimated that $PM_{2.5}$ pollution contributed to 15.5% (1.7 million) of all deaths in China in 2015 [7].

Ambient $PM_{2.5}$ concentrations are usually used for $PM_{2.5}$ exposure assessment in epidemiological studies [8–10]. However, most people spend more than 80% of their time indoors [11–13]. Therefore, the indoor $PM_{2.5}$ pollution level has a significant influence on human exposure to air pollution. The difference between indoor and outdoor $PM_{2.5}$ concentrations has become a source of measurement bias in epidemiological studies [14,15]. Some researchers discovered that the geographical heterogeneity in PM-related mortality observed in air pollution and health effects studies can be partially explained by the regional difference of indoor exposure to outdoor PM in the United States [16], Europe [17] and China [18]. Understanding the relationship between indoor and outdoor air pollution is essential to better characterize ambient

Abbreviations: $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 μm; SES, socioeconomic status; DALYs, disability-adjusted life-years; MicroPEM, micro personal exposure monitor; HEPA, high-efficiency particulate air; NAAQS, National Ambient Air Quality Standards; WHO, World Health Organization; AQG, Air Quality Guidelines; MEPC, the Ministry of Environmental Protection of China; YRD, Yangtze River Delta; CNY, Chinese Yuan.

* Corresponding author. School of the Environment, Nanjing University, 163 Xianlin Avenue, Nanjing 210023, China.
** Corresponding author. Chinese Academy for Environmental Planning, 8 Dayangfang, Beiyuan Road, Chaoyang District, Beijing 100012, China.
E-mail addresses: shaozhijuan@126.com (Z. Shao), jbi@nju.edu.cn (J. Bi), njumazw@163.com (Z. Ma), wangjn@caep.org.cn (J. Wang).

http://dx.doi.org/10.1016/j.buildenv.2017.09.002
0360-1323/

$PM_{2.5}$ exposure and health effects.

Indoor $PM_{2.5}$ pollution can arise from various sources both outdoors (e.g., vehicles, industry, heating emissions and atmospheric chemical reactions) and indoors (e.g., cooking, cleaning and dusting) [19]. Various studies have explored the relationship between indoor and outdoor $PM_{2.5}$ concentrations in urban areas in China, including Beijing [20,21], Tianjin [22], Nanjing [23] and Hong Kong [24], in a single season. Cao et al. [25] found that the indoor-outdoor relationship for $PM_{2.5}$ and its chemical components were different in summer and winter. Qi et al. [26] established two indoor $PM_{2.5}$ prediction models based on ambient data and discovered that the lagging effect of outdoor pollution on indoor levels was different in heating and non-heating seasons. The determinants of indoor $PM_{2.5}$ concentrations were related to the season [27]. However, to the best of our knowledge, few studies have been conducted to examine the determinants of seasonal indoor $PM_{2.5}$ pollution in China. According to the *Exposure Factors Handbook of Chinese Population (Adults)* [13], the indoor ventilation time is markedly different in summer, winter, and transition seasons (i.e., spring and fall). Ambient air pollution usually shows obvious seasonal variations in China [28]. The seasonal trends of outdoor $PM_{2.5}$ pollution and indoor ventilation frequency may influence the infiltration of outdoor $PM_{2.5}$ [29,30] and the diffusion of indoor $PM_{2.5}$ emitted by indoor sources [31].

In this study, we focus on the seasonal trends of indoor $PM_{2.5}$ concentrations and explore its determinants in urban residences in Nanjing. Nanjing is located in the western region of the Yangtze River Delta (YRD) and is one of the most developed and rapidly urbanized areas of China. However, the air quality conditions are poor, especially $PM_{2.5}$ [32,33]. This study will shed light on the current status of indoor $PM_{2.5}$ pollution in urban residences and provide a better understanding of the seasonal indoor-outdoor relationship of $PM_{2.5}$, which is essential for the accurate exposure assessment of air pollution. Moreover, the results will be useful for improving indoor air quality in homes and for reducing human exposure to $PM_{2.5}$ by modifying individual behavior patterns indoors.

2. Methodology

2.1. Study area and sites

The study was conducted in Nanjing, a major city of the YRD, in East China (N 31°14′~32°37′, E 118°22′~119°14′). Homes participating in this study were recruited by telephone interview and door-to-door surveys. A preliminary survey was performed to determine the construction date of the residences during recruitment. Single-stage stratified sampling was used, in which the residences in Nanjing were stratified into four groups based on the construction date of the building (before 1990, 1991–2000, 2001–2010 and after 2011). After informing the occupants of the objective of our research, 60 families joined this study. Among the 60 residences, 9 were built before 1990, 12 between 1991 and 2000, 14 between 2001 and 2010, and 25 after 2011. Apartment buildings were the main residence type in this study. Informed consent was obtained from each participant. The homes were randomly distributed in 8 urban districts in Nanjing: 20 in Xuanwu, 4 in Qinhuai, 2 in Gulou, 14 in Jianye, 6 in Qixia, 3 in Yuhuatai, 7 in Pukou, and 4 in Jiangning (Fig. 1).

2.2. Indoor and outdoor $PM_{2.5}$ monitoring

Nanjing has a subtropical and humid climate with a cold winter and hot summer. In transition seasons (i.e., spring and fall), the average temperature is comfortable, ranges from 15.7 °C to 23.6 °C [34]. Generally, air conditioning is not used in transition seasons [35], and people often ventilate by opening windows. Indoor ventilation times are similar in the transition seasons (i.e., spring and fall) in China, according to the *Exposure Factors Handbook of Chinese Population (Adults)* [13]. When windows are opened, outdoor-originating particles contribute more than 90% of the indoor $PM_{2.5}$ concentration [19]. Thus, the sampling period in this study was divided into three seasons: summer (June–August 2016), winter (December 2016–February 2017), and transition seasons (March–May/October–November 2016). Out of the 60 residences in this study, only 16 families participated across multiple season treatments. The families that dropped out were supplemented by newly recruited homes each season. Finally, 35 families were sampled in summer, 36 in winter, and 39 in transition seasons. It should be noted that a proportion of the dataset consists of non-independent data (i.e., observations from families that were sampled repeatedly across multiple seasons), which may have slightly inflated the Type I (false positive) error rate. The characteristics of the families in each season are given in Tables S1–S2. Indoor and outdoor $PM_{2.5}$ concentrations were measured simultaneously by micro personal exposure monitors (MicroPEM) (RTI International, Research Triangle Park, NC, USA), operated at a nominal flow rate of 0.5 L/min. The MicroPEMs were zeroed with an in-line high-efficiency particulate air (HEPA) filter and pre-calibrated with a TSI model 4143 mass flow meter (TSI, Inc., Shoreview, MN, USA) using the Docking Station software provided by RTI International. The indoor MicroPEMs were placed in the living room, approximately 1.5 m above the ground, away from open windows and doors. For outdoor sampling, the samplers were located on the open balcony outside the home. When an open balcony was not available at the home, the samplers were set on the windows and an inlet top cap of the sampler was used to connect tubing for outdoor $PM_{2.5}$ sampling. When two or three adjoining families were selected, only one outdoor monitoring site was set outside the two or three homes. Forty-eight hour indoor and outdoor measurements were taken simultaneously in each home. The PTFE filters (25 mm, 3.0 μm pore size, PALL, Mexico) and batteries in the MicroPEMs were replaced by our researchers every 24 h.

The real-time $PM_{2.5}$ mass concentrations measured by the MicroPEMs were calibrated using the gravimetric mass concentrations retrieved from the filters in the samplers. The result of the regression analysis showed that the two types of $PM_{2.5}$ mass concentrations agreed well ($R^2 = 0.86$, $p < 0.001$) (Fig. S1). Therefore, the real-time $PM_{2.5}$ mass concentrations presented in this paper have not been corrected to their gravimetric equivalent.

2.3. Questionnaires

A questionnaire with information on housing characteristics and SES was completed at each home (shown in the Supporting Information), including building height, construction date, floor area, building orientation, distance to the main traffic road, recent refurbishment, new furniture purchases, dwelling ownership, number of occupants, pet ownership, and household monthly income. Additionally, participants were asked to complete a time-activity questionnaire to obtain information on activities that would influence the indoor $PM_{2.5}$ level in their home during the sampling period, including opening living room windows, cooking, smoking indoors, and the use of air conditioners and air cleaners.

2.4. Data analysis

Descriptive statistical analyses were conducted for the indoor and outdoor $PM_{2.5}$ mass concentrations and possible indoor PM determinants. The Kruskal-Wallis H test was performed to compare